

DIFFUSE GALACTIC γ -RAYS: CONSTRAINING COSMIC-RAY ORIGIN AND PROPAGATION

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Abstract. We have developed a model which aims to reproduce observational data of many kinds related to cosmic-ray (CR) origin and propagation: direct measurements of nuclei, antiprotons, electrons and positrons, γ -rays, and synchrotron radiation. Our main results include evaluation of diffusion/convection and reacceleration models, estimates of the halo size, calculations of the interstellar positron and antiproton spectra, evaluation of alternative hypotheses of nucleon and electron interstellar spectra, and computation of the Galactic diffuse γ -ray emission. Recently our CR propagation code has been generalized to include fragmentation networks of arbitrary complexity. The code can now provide an alternative to leaky-box calculations for full isotopic abundance calculations and has the advantage of including the spatial dimension which is essential for radioactive nuclei. Preliminary predictions for sub-Fe/Fe, $^{10}\text{Be}/^9\text{Be}$ and $^{26}\text{Al}/^{27}\text{Al}$ are presented in anticipation of new experimental isotopic data. We show that combining information from classical CR studies with γ -ray and other data leads to tighter constraints on CR origin and propagation.

1. Introduction and the Modelling Approach

A numerical method for the calculation of Galactic CR propagation in 3D has been developed. Our program[‡] (SM98, MS98, MSR98, SMR00) performs CR propagation calculations for nuclei, antiprotons, electrons and positrons and computes γ -ray and synchrotron emission in the same framework. The 3D spatial approach with a realistic distribution of interstellar gas distinguishes it from leaky-box calculations. The basic spatial propagation mechanisms are diffusion and convection, while in momentum space energy loss and diffusive reacceleration are treated. Fragmentation and energy losses are computed using realistic distributions for the interstellar gas and radiation fields. The basic procedure is first to obtain a set of propagation parameters which reproduce the CR B/C and $^{10}\text{Be}/^9\text{Be}$ ratios; the same propagation conditions are then applied to all the CR species. Gamma-ray and synchrotron emission are then evaluated with the same model. We aim for a “standard model” which can be improved with new astrophysical input and additional observational constraints.

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‡ Our model (“GALPROP”) including software and datasets is available at <http://www.gamma.mpe-garching.mpg.de/~aws/aws.html>



GALPROP solves the Galactic CR propagation equation numerically on a grid in 3D with cylindrical symmetry, and the basic coordinates are (R, z, p) , where R is Galactocentric radius, z is the distance from the Galactic plane, and p is the total particle momentum. In the models the propagation region is bounded by $R = R_h$, $z = \pm z_h$ beyond which free escape is assumed. For a given z_h the diffusion coefficient as a function of momentum is determined by B/C for the case of no reacceleration; if reacceleration is assumed then the reacceleration strength (related to the Alfvén speed, v_A) is constrained by the energy-dependence of B/C. We include diffusive reacceleration since some stochastic reacceleration is inevitable, and it provides a natural mechanism to reproduce the energy dependence of the B/C ratio without an *ad hoc* form for the diffusion coefficient (e.g., Seo and Ptuskin, 1994). The distribution of CR sources is chosen to reproduce (after propagation) the CR distribution determined by analysis of EGRET γ -ray data (Strong and Mattox, 1996). The bremsstrahlung and inverse Compton (IC) γ -rays are computed self-consistently from the gas and radiation fields used for the propagation.

Tighter constraints on the parameters of CR propagation and source abundances can be obtained from consideration of all CR isotopes simultaneously. We have now been able to generalize the scheme to include CR reaction networks of arbitrary complexity. The scheme can hence potentially compete with leaky-box calculations for computation of isotopic abundances, while retaining the spatial component essential for radioactive nuclei, electrons and γ -rays. Even for stable nuclei it has the advantage of a physically-based propagation scheme with a spatial distribution of sources rather than an *ad hoc* path length distribution. It also facilitates tests of reacceleration.

The new extended approach for nuclei handles the reaction network explicitly (SM99b), as follows: (i) propagate primary species from an assumed set of source abundances, (ii) compute the resulting spallation source function for all species, (iii) propagate all species using the primary and spallation sources. Steps (ii) and (iii) are iterated until converged. After the second iteration the result is already accurate for the pure secondary component, after the third iteration it is accurate for tertiaries, and so on. Hence in practice only a few such iterations are necessary for a complete solution of the network. The method is more time-consuming than the simpler approach we used before, where multiple progenitors and tertiary etc. reactions were handled by weighting the cross-sections, since many more species are included and because of the several iterations required.

2. Probes of Interstellar Propagation

Measurements of nucleons in CR provide a basis for probing interstellar propagation and determining the halo size. The ratio of stable secondary to primary nuclei is often used to constrain such parameters as the diffusion coefficient, reaccelera-

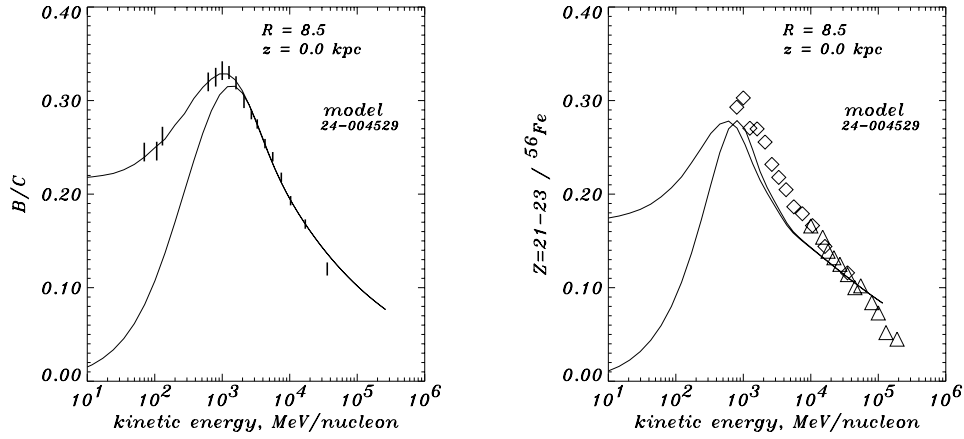


Figure 1. Left: B/C interstellar and modulated to 500 MV for diffusive reacceleration model with $z_h = 4$ kpc. Data compilation: Webber et al. (1996). Right: The same for sub-Fe/Fe. Data: \diamond – Engelmann et al. (1990), \triangle – Binns et al. (1988).

tion strength and/or convection velocity, while long-lived radioactive species can be a probe of the extent of the propagation volume.

To constrain the parameters of propagation we use the B/C ratio which is measured over a wide energy range. In diffusion/convection models with a diffusion coefficient which is a simple power-law in momentum a good fit is *not* possible; the basic effect of convection is to reduce the variation of B/C with energy, and although this improves the fit at low energies the characteristic peaked shape of the measured B/C cannot be reproduced. Although modulation makes the comparison with the low energy data somewhat uncertain, the fit is unsatisfactory. We concluded therefore that convection does not seem to work in detail, but requires an artificial break in the diffusion coefficient. If instead we consider diffusive reacceleration, the peak is produced rather naturally (as many people have pointed out) so that we rather prefer this solution.

Propagation parameters[†] for a model with reacceleration are: halo size $z_h = 4$ kpc, $v_A = 20$ km s⁻¹, diffusion coefficient $D = D_0 \beta(p/p_0)^{1/3}$, where $D_0 = 6.75 \times 10^{28}$ cm² s⁻¹, and $p_0 = 3$ GeV.

We have applied the method to a network of 87 nuclei from protons to Ni, including explicitly all stable species and radioactive species with half-life more than 10^5 years. Isotopic cross sections are based on measured values where available. Otherwise we use the Webber et al. (1990) cross-section code. Source abundances are from DuVernois and Thayer (1996), with solar isotopic ratios within a given element.

[†] The diffusion coefficient, adjusted to fit B/C, differs slightly from that used in the original work for the same z_h (SM98), reflecting the more detailed treatment and updated cross sections.

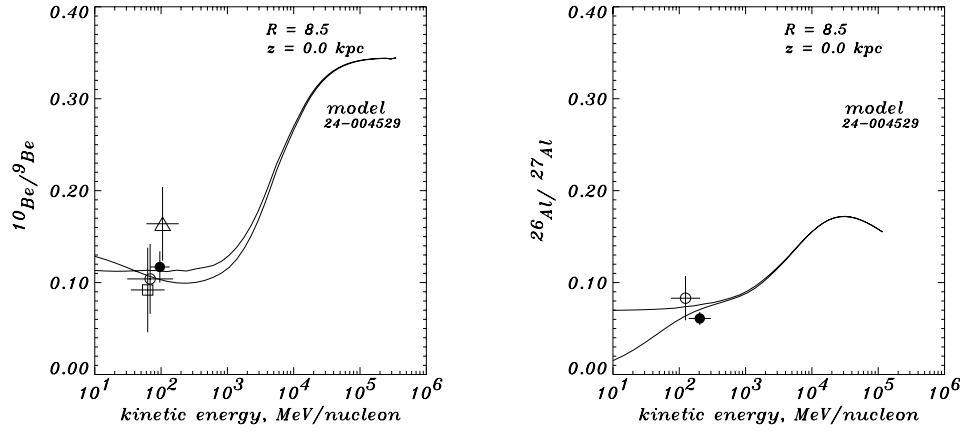


Figure 2. Model interstellar and modulated (500 MV) ratios. *Left:* $^{10}\text{Be}/^9\text{Be}$. Data from Lukasiak et al. (1994a) (\square – Voyager-1,2, \circ – IMP-7/8, \triangle – ISEE-3) and Connell (1998) (\bullet – Ulysses). *Right:* $^{26}\text{Al}/^{27}\text{Al}$. Data: \circ – Lukasiak et al. (1994b), \bullet – Simpson and Connell (1998). Note that the data points shown are at the measured (not interstellar) energies.

Figure 1 shows B/C and sub-Fe/Fe. This model with reacceleration reproduces the sub-Fe data reasonably well considering that the model was adjusted only to fit B/C. The deviation from the observed sub-Fe/Fe shape is however noticeable, as discussed by Webber (1997).

Figure 2 shows examples of radioactive species. Modulation is for nominal values of the modulation parameter but this has little effect on the comparison due to the small energy dependence of these ratios in the 100–1000 MeV/nucleon range. In SM98 we obtained a range $4 \text{ kpc} < z_h < 12 \text{ kpc}$ for the halo height; in the present improved model the $^{10}\text{Be}/^9\text{Be}$ and $^{26}\text{Al}/^{27}\text{Al}$ predictions are consistent with this.

Recently, Webber and Soutoul (1998) and Ptuskin and Soutoul (1998) have obtained $z_h = 2 - 4 \text{ kpc}$ and $4.9^{+4}_{-2} \text{ kpc}$, respectively, and our results are consistent with these.

Figure 3 shows computed fluxes of all the included isotopes. This result is illustrative of the method but not to be taken as predictions for evaluation purposes.

3. Probes of the Interstellar Nucleon Spectrum: Diffuse Continuum γ -rays, Antiprotons and Positrons

Secondary e^+ 's and \bar{p} 's in Galactic CR and some part of the diffuse Galactic γ -rays are produced in collisions of CR particles with interstellar matter[†]. Because they are secondary, they reflect the *large-scale* nucleon spectrum independent of local

[†] Contributions from possible nearby source(s) of positrons (e.g., Aharonian et al., 1995) and WIMP annihilation (e.g., Bottino et al., 1998; Baltz and Edsjö, 1998; MS99) are also discussed.

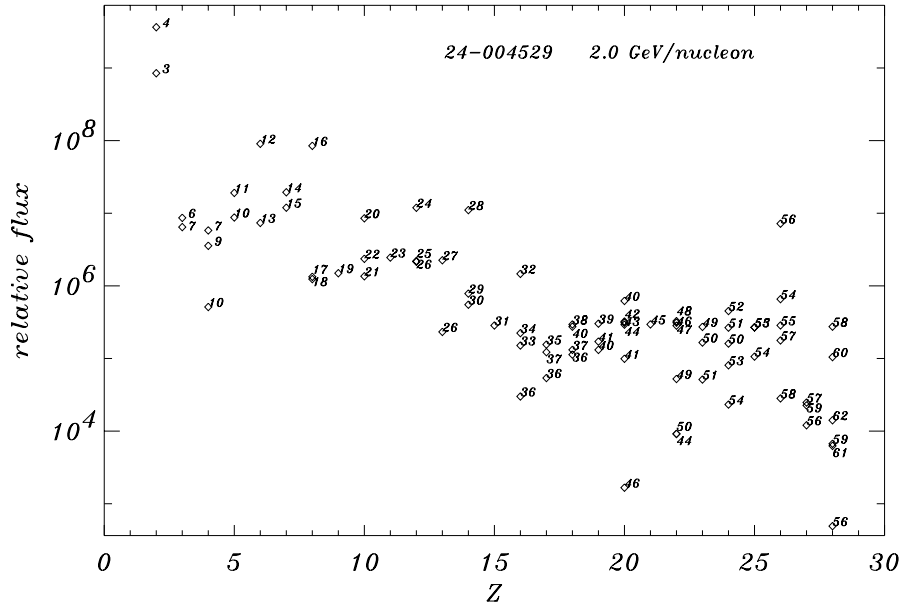


Figure 3. Model isotopic fluxes at 2 GeV/nucleon (SM99b) as function of Z ; individual A values are marked.

irregularities in the primaries and thus provide an essential check on propagation models and also on the interpretation of diffuse γ -ray emission (MS98, MSR98, SMR00). These are an important diagnostic for models of CR propagation and provide information complementary to that provided by secondary nuclei. However, unlike secondary nuclei, \bar{p} 's and e^{+} 's reflect primarily the propagation history of the protons, the main CR component.

The most direct probe of the interstellar proton spectrum is perhaps provided by diffuse γ -rays, but an essential and *a priori* unknown part of the emission is produced by CR electrons via IC scattering. The latter depends on many details of propagation in the Galaxy as well as distributions of the magnetic and radiation fields. Moreover, because of large electron energy losses the average electron spectrum in the Galaxy can differ substantially from what is measured locally.

Recent results from both COMPTEL and EGRET indicate that IC scattering is a more important contributor to the diffuse emission than previously believed. The puzzling excess in the EGRET data > 1 GeV relative to that expected for π^0 -decay has been suggested to originate in IC scattering from a hard interstellar electron spectrum (e.g., Pohl and Esposito, 1998; SM99a), or from a harder average nucleon spectrum in interstellar space than that observed directly (e.g., Mori, 1997). Our combined approach allows us to test these hypotheses (SMR00).

Our calculations show that the suggestion of a hard nucleon spectrum provides better agreement with EGRET measurements, but conflicts with data by producing

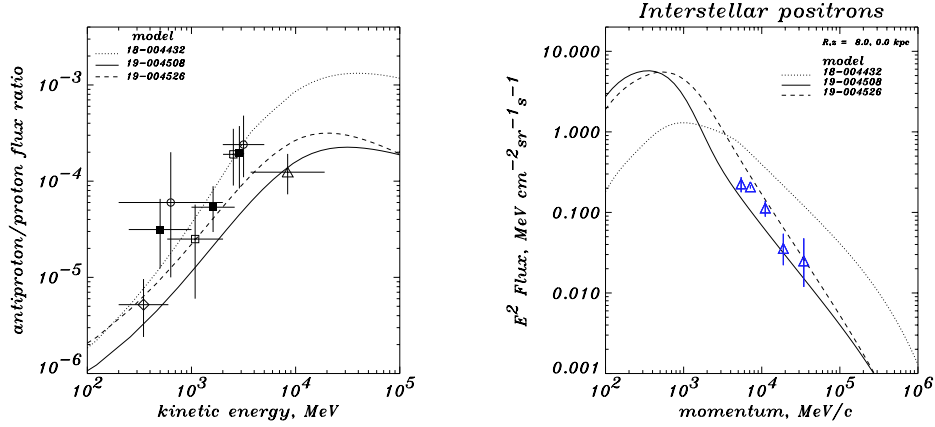


Figure 4. Left: Interstellar \bar{p}/p ratio for different ambient proton spectra (MSR98, SMR00) compared with data. Solid line: “conventional”, dotted line: “hard nucleons”, dashed line: “best model”. Data (direct measurements): see references in MSR98. Right: Interstellar spectra of e^+ s for different ambient proton spectra (SMR00) compared with data. Lines are coded as on the left. Data (direct measurements): Barwick et al. (1998).

too much \bar{p} and e^+ (Figure 4). The hard electron spectrum hypothesis looks more plausible but still the agreement with γ -ray data is not too good.

Our best model so far has an electron injection spectral index of -1.8 , which after propagation with reacceleration provides consistency with radio synchrotron data (a crucial constraint). Following Pohl and Esposito (1998), for this model we do *not* require consistency with the locally measured electron spectrum above 10 GeV since the rapid energy losses cause a clumpy distribution so that this is not necessarily representative of the interstellar average. For this case, the interstellar electron spectrum deviates strongly from that locally measured, and also the nucleon spectrum at low energies is slightly modified to obtain an improved fit to the γ -ray data. Because of the increased IC contribution at high energies, the predicted γ -ray spectrum can reproduce the overall intensity from 30 MeV – 10 GeV (Figure 5) (SMR00).

Our calculations of the antiproton/proton ratio and spectra of secondary e^+ s for this model (with reacceleration) are shown in Figure 4. The predictions are larger than the conventional model, in which the electron and nucleon spectra are adjusted to agree with local measurements, but are still consistent with the \bar{p} and e^+ measurements. The analysis of the latitude and longitude γ -ray distributions shows that such a model with large IC component can indeed reproduce the data (SMR00).

None of our models fits the γ -ray spectrum below ~ 30 MeV as measured by the Compton Gamma-Ray Observatory (Figure 5). This is the consequence of our requirement to be consistent with synchrotron data. In order to fit the low-energy part as diffuse emission, without violating synchrotron constraints (SMR00), we

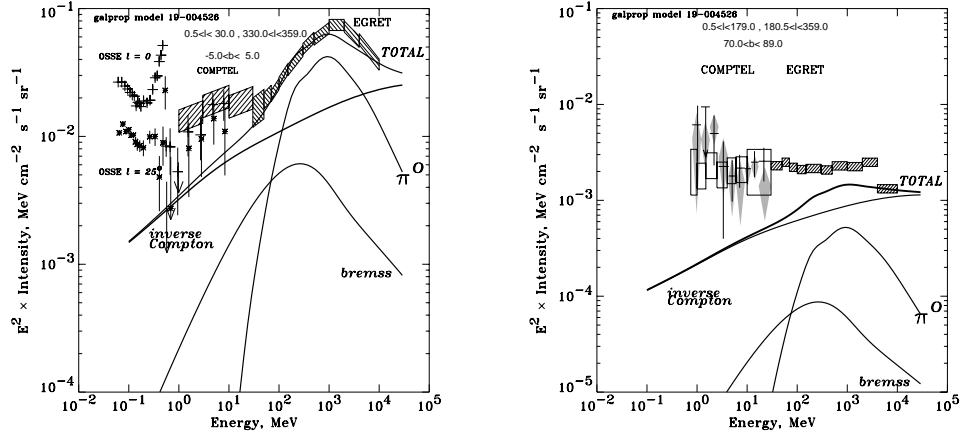


Figure 5. *Left:* Gamma-ray energy spectrum of the inner Galaxy ($300^\circ \leq l \leq 30^\circ$, $|b| \leq 5^\circ$) compared with our best model calculations ($z_h = 4$ kpc). Curves show the contribution of IC, bremsstrahlung, and π^0 -decay, and the total. Data: EGRET (Strong and Mattox, 1996), COMPTEL (Strong et al., 1999), OSSE ($l = 0, 25^\circ$: Kinzer et al., 1999). *Right:* Energy spectrum of γ -rays from high Galactic latitudes ($|b| \geq 70^\circ$, all longitudes). Data: see references in SMR00.

require a rapid upturn in the CR electron spectrum below 200 MeV. However, in view of the energetics problems (Skibo et al., 1997), a population of unresolved sources seems a more probable origin for the emission and would be the natural extension of the low energy plane emission seen by OSSE (Kinzer et al., 1999) and GINGA (Yamasaki et al., 1997).

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Note added in proof. Recently, new high-energy antiproton data on both \bar{p}/p ratio and absolute flux have become available (Bergström et al., 2000; Basini et al., 1999). These data agree with our conventinal model and best model (with slightly modified nucleon spectrum), therefore providing a strong evidence against the hypothesis of a hard nucleon spectrum in the Galaxy.

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